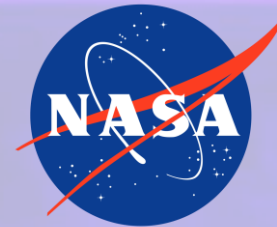


Implementation of an Unsteady PSP System in the NASA TDT

Daniel Reese, Sarah Peak, Kyle Goodman, Neal Watkins
NASA Langley Research Center

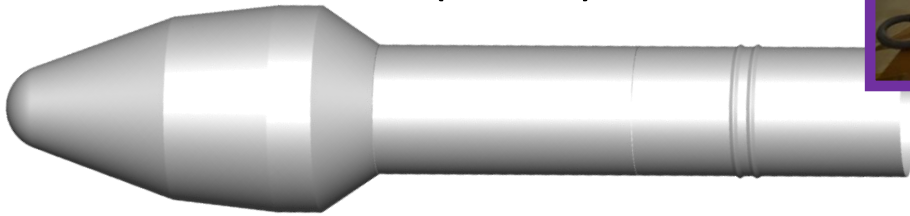
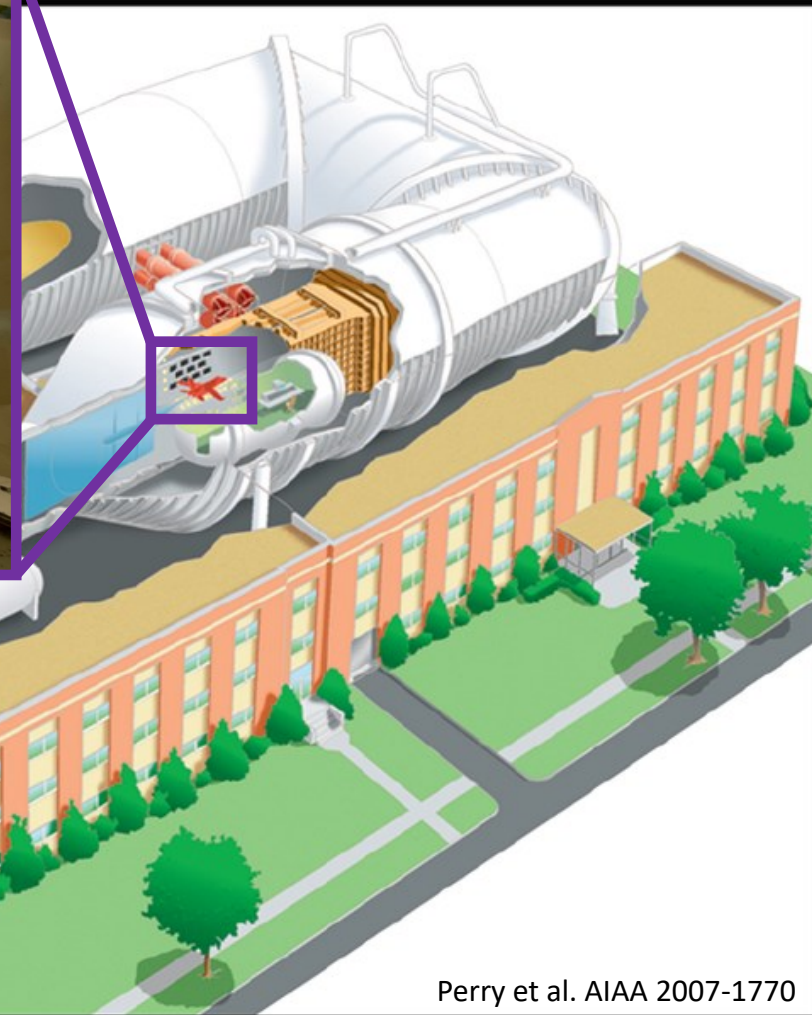


daniel.reese@nasa.gov

Wind Tunnel Facility & Launch Vehicle Model

Transonic Dynamics Tunnel (TDT)

- Continuous, closed-circuit
- 16'×16' slotted test section
- $0.01 \text{ atm} < P < 1 \text{ atm}$
- $0 < \text{Mach} < 1.2$
- Max Reynolds number of:
 - $9.6 \times 10^6 / \text{ft}$ (in R-143a)
 - $3 \times 10^6 / \text{ft}$ (in air)

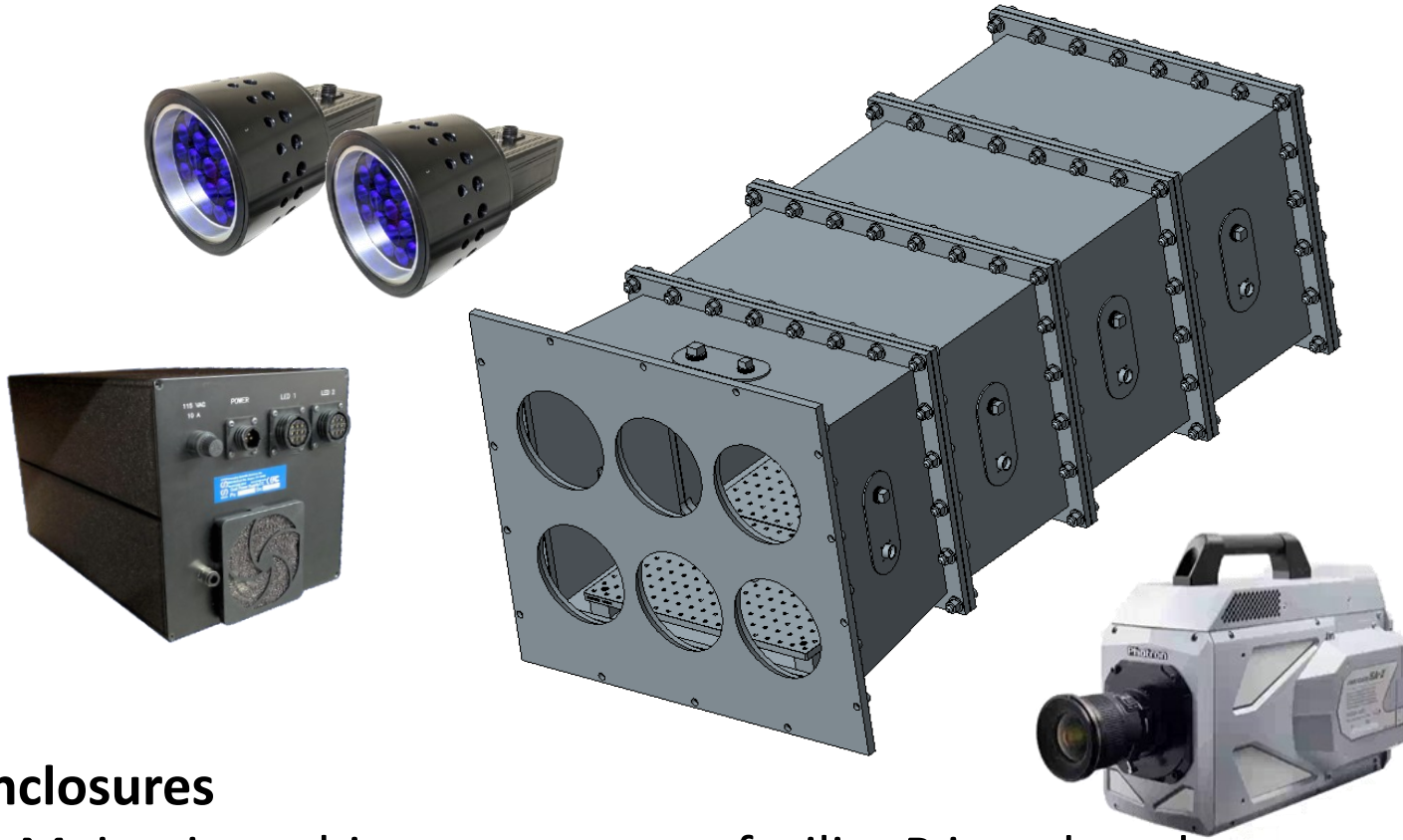


Launch Vehicle Model

- Generic hammerhead used by Coe and Nute (NASA TM X-778, 1962)
- 17.4" long payload section
- 56 Kulites & 14 static pressure taps

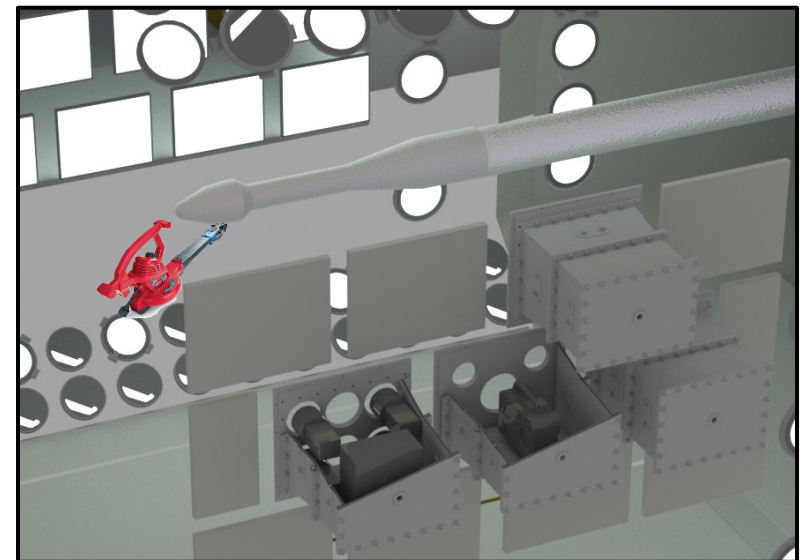
Perry et al. AIAA 2007-1770

Environmental Enclosures

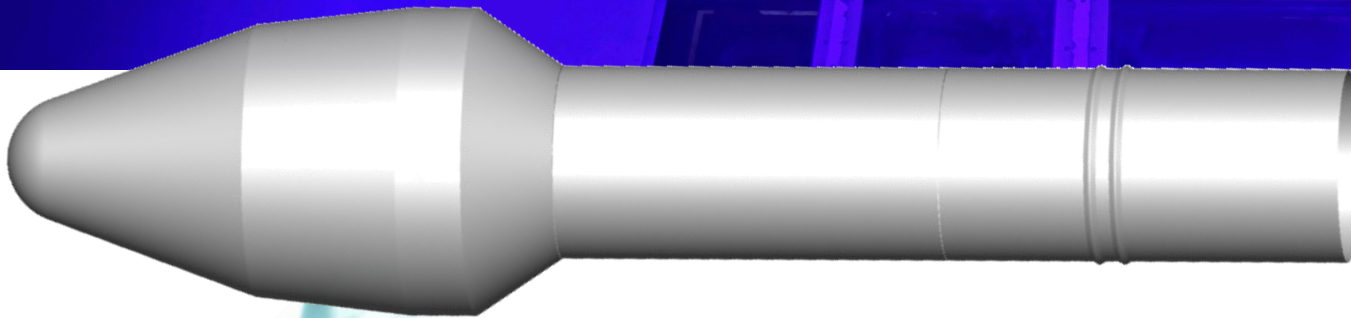
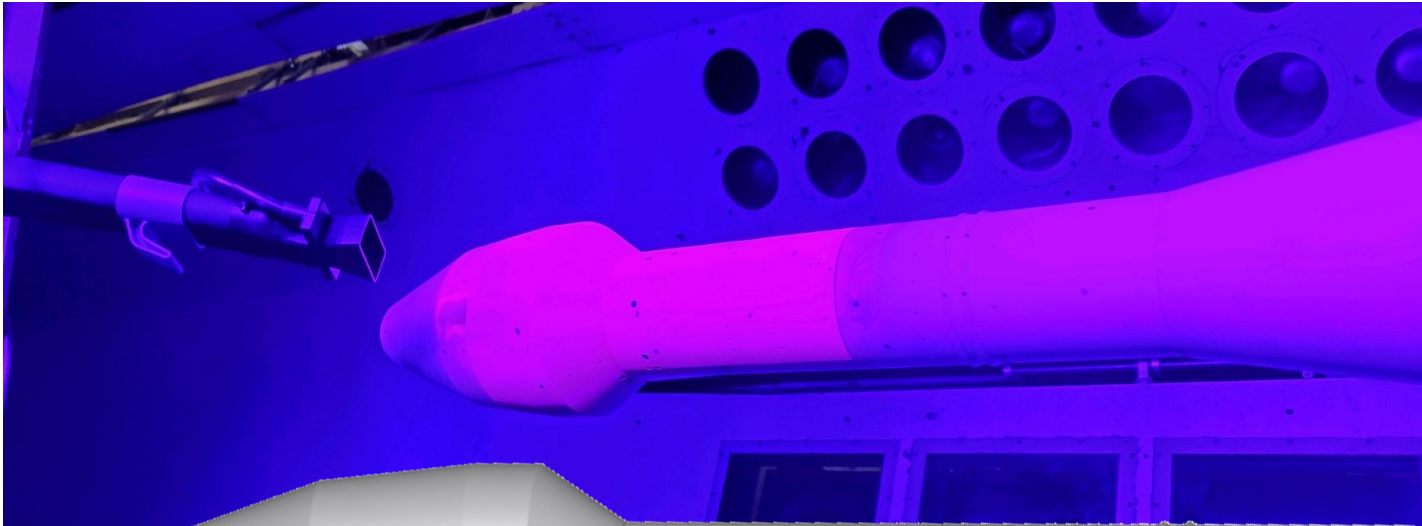


Enclosures

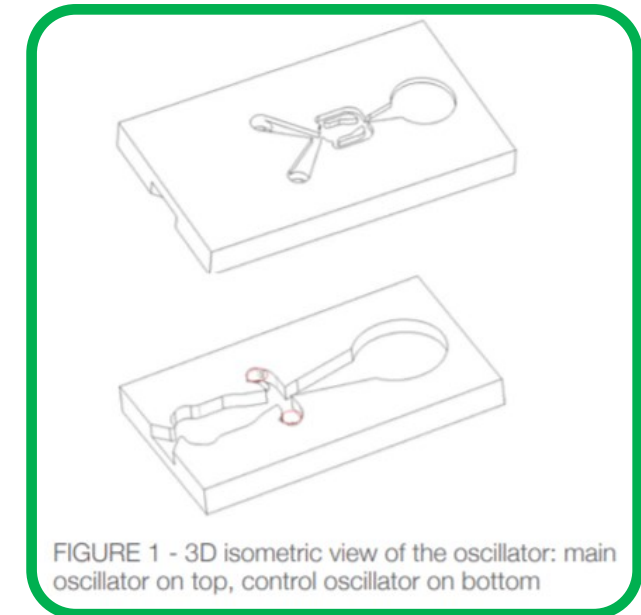
- Maintain ambient pressure as facility P is reduced
- Provide constant supply of cooling air for internal components
- Allow for remote-operation (from control room) of all equipment housed within



Unsteady Flow System



Leaf blower with **fluidic oscillator attachment** creates impinging jet with known frequency independent of amplitude



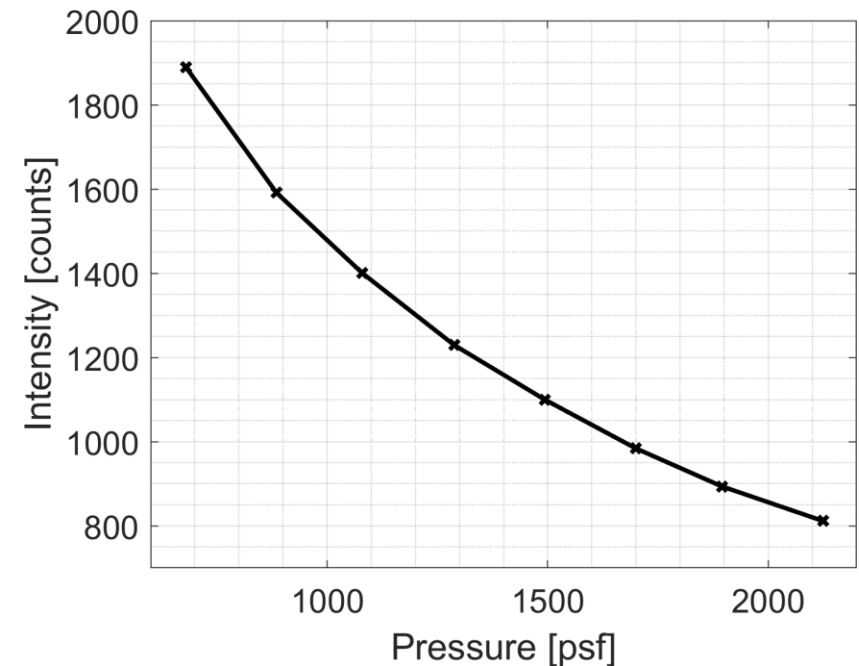
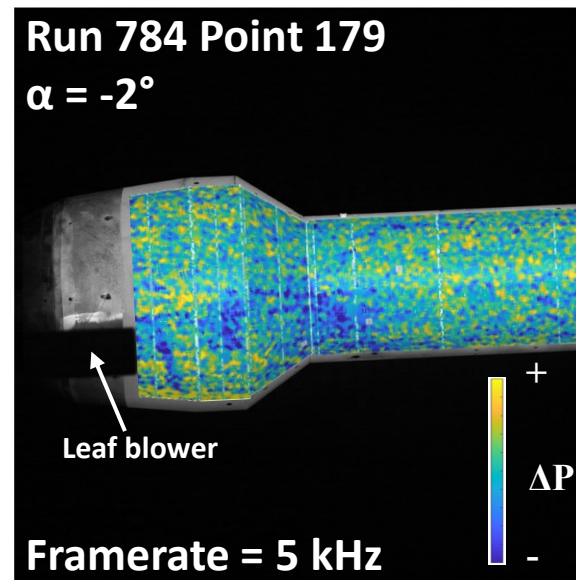
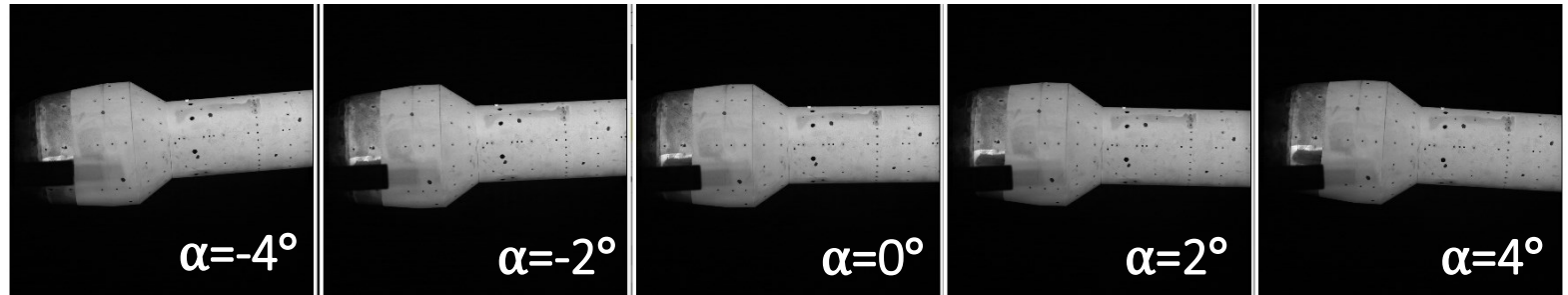
<https://technology.nasa.gov/patent/LAR-TOPS-36>

<https://doi.org/10.1103/APS.DFD.2015.GFM.V0015>

Test Objectives

uPSP measurements obtained at several frame rates, tunnel conditions, and model attitudes in TDT

- Vary AOA
 $-4^\circ < \alpha < 4^\circ$
- Vary pressure
 $565 < P < 2124$ psf
- Vary framerate
 5 & 10 kHz
- Data processing on NAS
 Map measurements to grid
 Convert: I \rightarrow Pressure
- Post-processing
 Filter in time & space
 Kulite comparison
 Dynamic mode decomp.



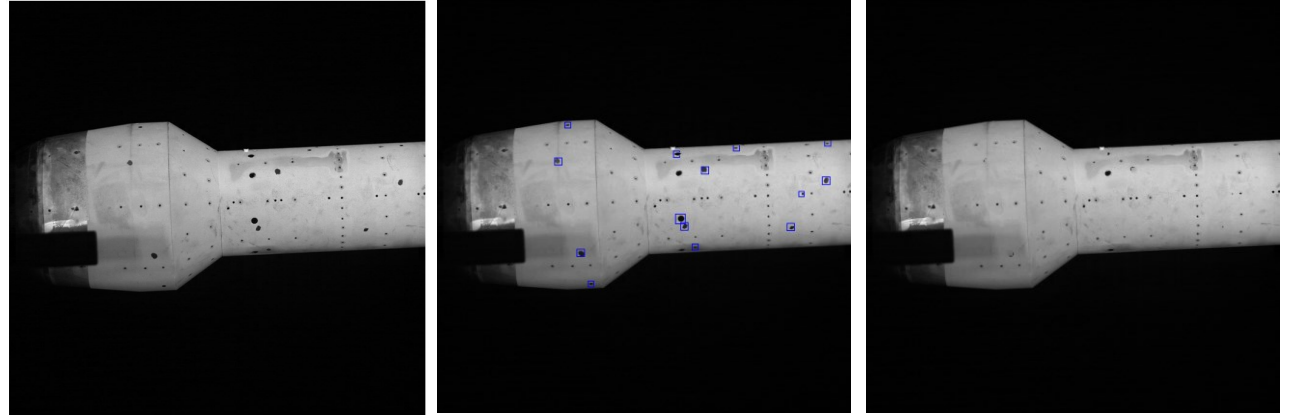
Data Processing

Data processing on NASA Advanced Supercomputer (NAS)

- Collaborative effort with NASA Ames
- Convert intensity movies to unsteady pressure mapped to grid

Phase 1: Image Preparation

- Calibration capturing relative orientation of camera and test article
 - First image only
- Data at oblique angle $>75^\circ$ removed from calculation
- Patch regions of “bad” data (e.g. registration targets, unpainted region)



Phase 2: Intensity Mapping

- Account for small model motion between frames by warping all subsequent images to align with first frame
- Project each warped image onto the model grid

Phase 3: Conversion to Pressure

- Calculate intensity fluctuations for each frame relative to average of all frames

$$P = \left(\frac{I_{ref}}{I} - 1 \right) * Gain$$

$$Gain = a + bT + cT^2 + (d + eT + fT^2) * P_{ss}$$

$$T = r(T_0 - T_\infty) + T_\infty \quad r = 0.896$$

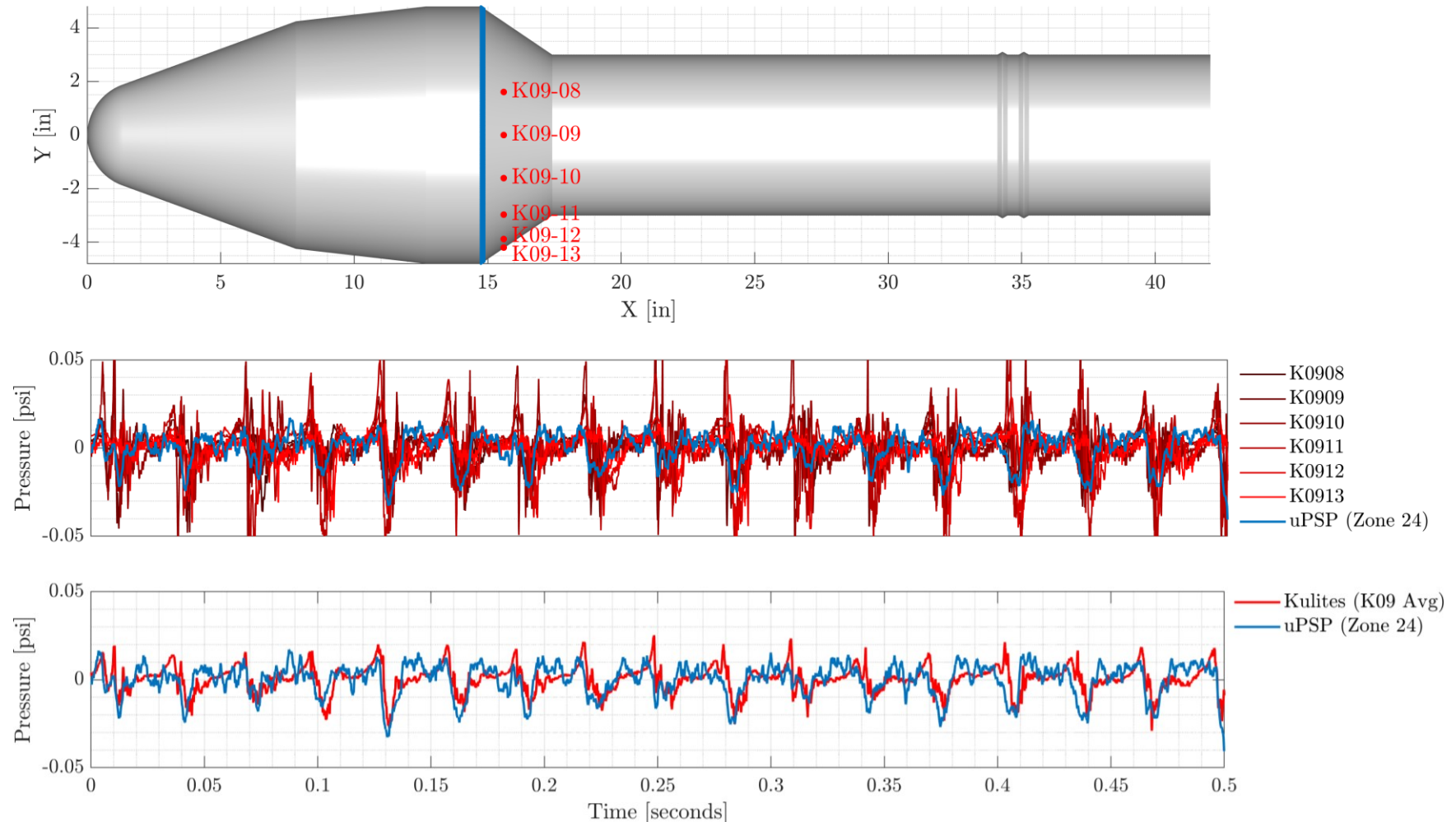
Unsteady pressure obtained from raw intensity data

Kulite Comparison: Time History

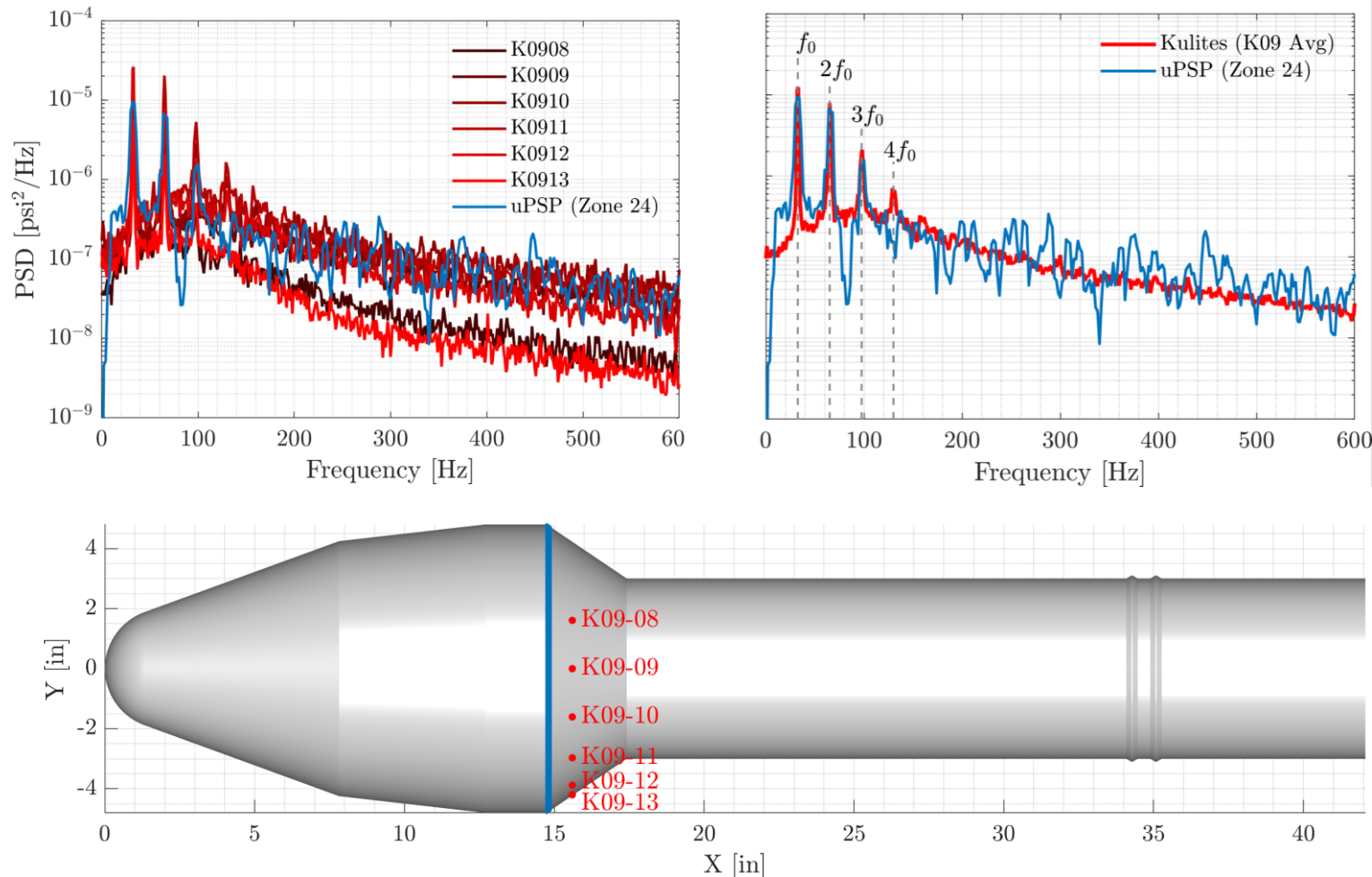
Δ Pressure Histories

- Zone-averaged PSP shows agreement with Kulite average
- Individual Kulites show spatial-dependence of pressure disturbance
- Better agreement likely achievable with local averaging around unsteady pressure tap

Small unsteady pressure disturbance resolved by uPSP system



Kulite Comparison: Spectral Analysis



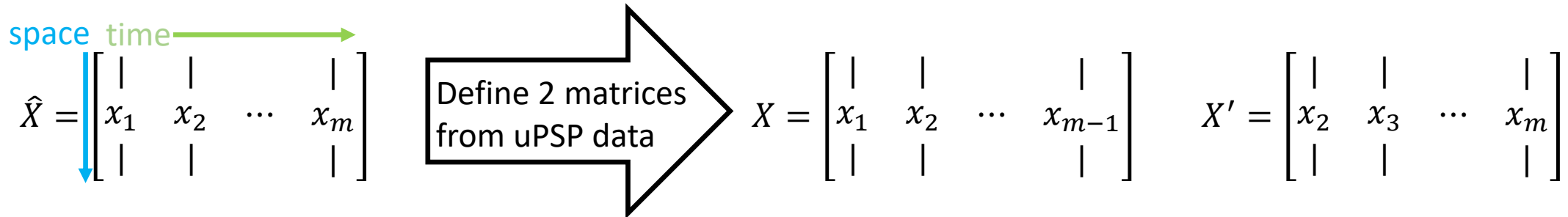
Power Spectra

- Zone-averaged PSP shows agreement with Kulite average
- Individual Kulites show spatial-dependence of pressure disturbance
- Fourth harmonic lost to noise in uPSP measurements

Fundamental frequency
(+ higher harmonics)
measured by uPSP system

Dynamic Mode Decomposition: Background

DMD is a dynamical system of coupled **spatial** **temporal** modes

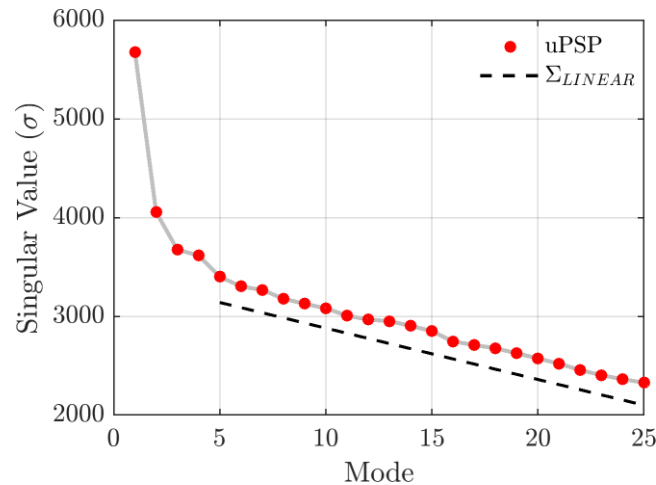


Today, this is a ~370k×45k matrix

DMD tries to find a best fit linear operator A that advances X into X'

$$X' \approx AX \quad \text{In our case, } A \text{ is } \sim 370\text{k} \times 370\text{k} \rightarrow 137\text{B entries}$$

Singular value decomposition (SVD) of X :



Reconstruct data using only dominant modes:

$$X = U\Sigma V^* \rightarrow X' = AU\Sigma V^*$$

Project A onto leading modes:

$$U^* X' V \Sigma^{-1} = U^* A U = \tilde{A}$$

Eigenvalue decomposition of \tilde{A} :

$$\tilde{A} W = W \Lambda$$

$$\Phi = X' V \Sigma^{-1} W$$

Decouple space and time

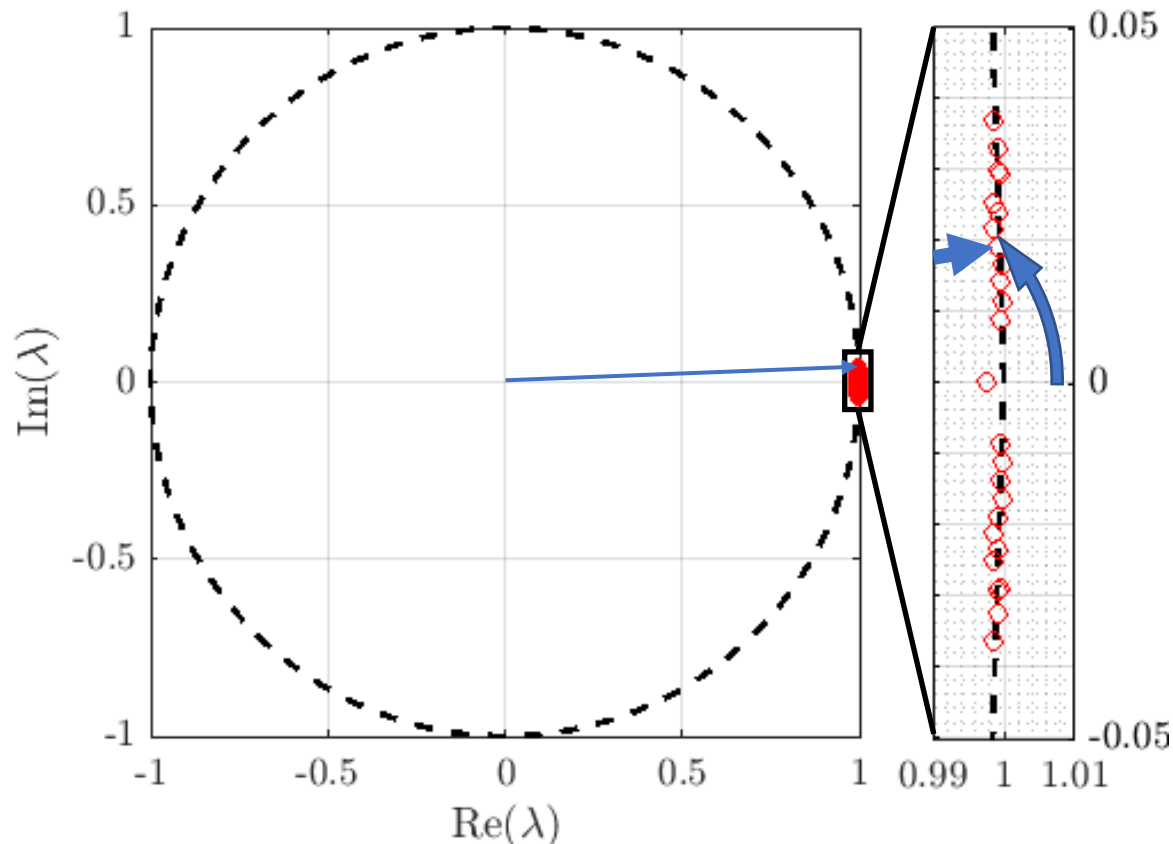
$$\hat{Y}(t) = \Phi \Lambda^t z_0$$

Continue analysis using only the r “most important” modes.

Today: $r=25$, so \tilde{A} is only 25×25 .

We have leading eigenvalues and eigenvectors of A without ever having to compute A

Temporal DMD Modes



25 modes consist of 12 complex conjugate pairs and one real value

Radial distance associated with growth rate

- Inside unit circle = decay
- Outside unit circle = growth
- On unit circle = oscillation

Angle determines frequency of associated mode

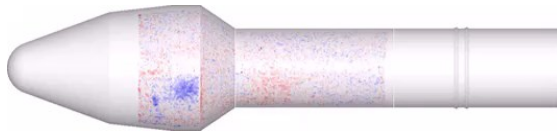
DMD eigenvalues (Λ) relate to temporal characteristics

Spatial DMD Modes

DMD eigenvectors (Φ) relate to spatial structures involved in the modal dynamics

“Eigen pressure distributions” show dominant spatial coherent modes

Real



Modes 1/2



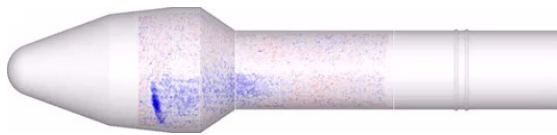
Modes 3/4



Modes 5/6

+ Higher Modes

Imaginary



Recall each (Φ) related to associated (Λ) so frequency of each mode is known

DMD Reconstruction

Now combine **space** (Φ) and **time** (Λ) by reconstructing uPSP data...

Filtering through DMD

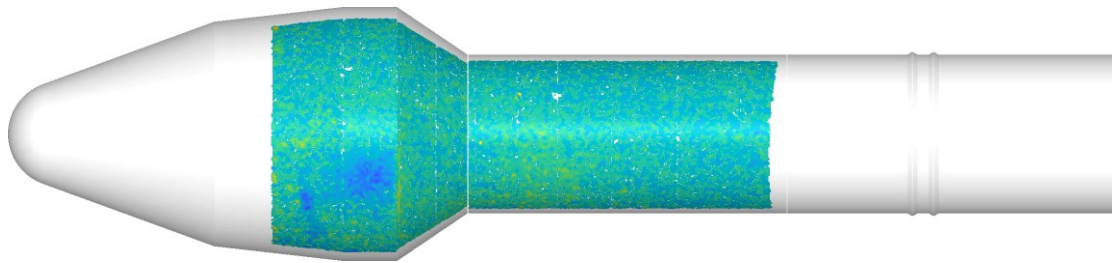
Reconstruction of our data using only $r=25$

dominant modes: $\hat{Y}(t) = \Phi \Lambda^t z_0$

Filtering in space and time

Moving average filter in time (75 frames = 15 ms)

2D median filter in space (4x4 pix)



Reconstructed uPSP measurements show improved noise reduction



Future Work

- Continue building on the post-processing tools developed for uPSP analysis
- Apply uPSP system to actual “wind on” test in TDT using the Coe model
- Determine the O₂ concentration needed to perform uPSP in a low-pressure R134a environment
- Apply all lessons learned for an upcoming experimental campaign for the space launch system (SLS)

The best is yet to come!